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13. ABSTRACT *(Maximum 200 words)*

This research was concerned with stochastic and statistical characterizations of quasi-periodic random processes, such as those associated with rotating machinery. The value of such characterizations includes enhanced abilities in condition monitoring for purposes of safety and performance. Major achievements of this research effort include (i) characterization of the influence of period uncertainty on estimation of a periodic time/frequency spectrum associated with a nominally wide sense cyclostationary (wsc) process, (ii) large sample distribution descriptions for the AR(p) and MV(p) spectral estimators for processes with mixed spectrum, (iii) a time-to-angle transformation method to better accomodate period variability, combined with an improved method for tracking real sinusoids with slowly varying frequency, (iv) greater insight into issues related to application of advanced spectral analysis methods for characterizing random processes associated with engines, compressors, and helicopter drivetrains, (v) a Matlab-based virtual signal analyzer which incorporates a number of our results in a user-friendly fashion, and (vi) development of research collaborations and workshops which serve to bring signal processing problems associated with rotating machinery to a broader base of researchers in industry, defense and academic institutions.

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SECTION A

EXECUTIVE SUMMARY

Rotating machinery comprises the most important class of systems associated with power plants, transportation, and manufacturing. With the dramatic increase in technology and economic pressure, the performance demands related to rotating machinery have made it essential that advanced diagnostic systems capable of early detection and identification of faults and changing conditions associated with reduced performance be developed. These diagnostic systems must not only take advantage of the most advanced theories, but they must be user-friendly. The value of advanced techniques is all too often compromised by (i) failure to take real world conditions which might violate theoretical assumptions into account, and (ii) the inability of applications engineers to apply them to real world problems. Having said this, the goal of the research program, the results of which are summarized in this report, was threefold: first, to develop a rigorous mathematical approach that would take greater advantge of the quasi-periodic structure of phenomena such as rotating machinery; second, to integrate the development of this approach with particular real world applications which might serve to suggest the extent to which assumptions related to the theory being developed might hold in practice, and hence guide the research direction; and third, to develop research collaborations with researchers in other disciplines who might be able to provide new and valuable perspectives, and who might also directly value from the development. Not only does this collaboration tend to preclude the "re-invention of the wheel" at a time when it is extremely difficult for researchers in one area to keep apprised of related mathematical problems and results in other disciplines, it also supports cross fertilization which can be mutually beneficial.

The approach that was taken in this effort was based on the fact that very often periodic stationary processes include two distinct components, namely, point spectrum associated with deterministic processes, and continuous spectrum associated with regular random processes. Interestingly, traditional methods of spectral analysis, which have been used in relation to rotating machinery for decades, are in fact ill-conditioned in relation to random processes having such a mixed spectrum. Another apsect of our approach which distinguishes it from not only traditional methods, but from all methods proposed to date, is the use of an entire family of spectral estimators, as opposed to a single best estimator, to characterize the spectral information. The mathematical foundation for this approach was developed prior to this research effort. The major results of this research effort include the following:

(i) characterization of the influence of period uncertainty on estimation of a periodic time/frequency spectrum associated with a nominally wide sense cyclostationary (wsc) process,

(ii) large sample distribution descriptions for the AR(p) and MV(p) spectral estimators for processes with mixed spectrum,

(iii) a time-to-angle transformation method to better accommodate period variability, combined with an improved method for tracking real sinusoids with slowly varying frequency.

(iv)greater insight into issues related to application of advanced spectral analysis methods for characterizing random processes associated with engines, compressors, and helicopter drivetrains,

(v)a Matlab-based virtual signal analyzer which incorporates a number of our results in a user-friendly fashion,

(vi) development of research collaborations and workshops which serve to bring signal processing problems associated with rotating machinery to a broader base of researchers in industry, defense and academic institutions.

SECTION B TABLE OF CONTENTS

SECTION

C. SUMMARY OF RESEARCH RESULTS

C1. BACKGROUND

A discrete time random process, X_t, is said to be a *mixed process* if $X_t = S_t + N_t$, where S_t is a sum of sinusoids and where N_t has $R_N(t, t+\tau)$ which is square summable in τ for any fixed t. In the case where N_t is *wss*, define the unbiased lagged-product autocorrelation estimator

$$\widehat{R}_x(\tau) = (1/N)\sum_{t=0}^{N-1} X_t X_{t+\tau}. \tag{1}$$

The following large sample result obtained in 1994 by Li *et al.* [LKY] for a mixed wss process, X_t is the basis of our key theoretical results.

Theorem 1. [LKY]. *Let x_t be a wss process with point spectrum at $\{\omega_m\}$, and with a Gaussian regular process. Let* $\mathbf{r}_p = [r(0), ..., r(p)]$ *with* r(k) in (2), *and let* $\widehat{\mathbf{r}}_p$ *be the unbiased lagged-product estimator of* $\mathbf{r}_p$. *Then* $\sqrt{N}(\widehat{\mathbf{r}}_p - \mathbf{r}_p) \sim N(0, \Sigma)$ where $\Sigma = \{\sigma_{j,k}\}$

where $\sigma_{j,k} = [\sum_{m=1}^{q} 2A_m^2 cos(j\omega_m)cos(k\omega_m)]\sum_{\tau=-\infty}^{\infty} r(\tau)cos(\omega_m\tau) + \sum_{\tau=-\infty}^{\infty}\{r(\tau)r(\tau+j-k) + r(\tau+j)r(\tau-k)\}$.

The above theorem is, in our belief, a major breakthrough, in that it is the first such result related to the use of the lagged-product autocorrelation estimator for mixed processes. It is well known that sinusoids appear as Dirac delta functions in a spectral density representation. Practically speaking, they contribute to a spectral density approximation, based on a finite number of correlation lags, peaks whose widths and amplitudes are a function of the number of lags used. In fact, as the number of lags approaches infinity, the peaks become unbounded. Consequently, if one is unaware of the presence of sinusoids, then one may be easily misled in conducting spectral analysis and system identification (see, e.g. [LSLJ). It follows that an essential ingredient of analysis of any spectral analysis methodology for processes which have *mixed spectrum* is a method to decompose the process being studied into its continuous and point spectrum components. A limited number of methods have been proposed for this purpose, the majority of which assume the regular component to be white. The method of Thompson [THO], which is perhaps the most well known, does not require the regular portion to be white. The convergence-based method of [FFS], which we have found to be valuable in a wide variety of real world settings, is the method we have focused on in this work for detecting sinusoids. It has a number of advantages over Thompson's method. One is that it does not rely on a single spectral estimate, but rather on an entire family of estimates. This allows for a much more visual interpretation. Second, and more important, it is equally valid for a large class of *nonstationary* processes [FRS]. The family of spectra studied in [FFS] have been labeled variously, the Capon, maximum likelihood, and minimum variance (MV) spectra. Here, we will use the MV terminology. The MV(n) spectrum for a scalar process X_t is defined as

$$MV_n(\omega) \triangleq (\boldsymbol{e}^*\boldsymbol{R}^{-1}\boldsymbol{e})^{-1} = [\sum_{k=0}^{n} AR_k(\omega)^{-1}]^{-1} \tag{2}$$

where, e=e(ω)=[1, $e^{i\omega}$, ..., $e^{in\omega}$]^{tr}, $\boldsymbol{R} = \{R(j-k); j,k = 1, ..., n\}$, and * denotes the conugate transpose. It is attractive from a spectral analysis perspective, since it implies that AR and MV spectra may be computed jointly, with little additional computational effort. When first proposed by Capon [CAP], and subsequently shown by Lacoss [LAC] to have less resolving power than the AR spectrum, the MV spectrum was generally viewed as a possible alternative to the AR spectrum. However, the result of [FFS], namely that (2) converges to the *point* spectrum as $n \to \infty$, suggests that the AR and MV spectra actually complement each other in mixed spectrum analysis.

C2. THEORETICAL RESULTS

The majority of the results summarized in this section were first documented in [LAU] and [LIU]. They have also been submitted for publication [LAS], [LSW], [LIS]. We first present some large sample results pertaining to AR and MV spectral estimators for mixed processes.

Theorem 2.[LAU] *Let $\widehat{S}_p(\omega)$ be the AR(p) spectral estimator for x_t, and let $S_p(\omega)$ be the corresponding AR(p) approximant obtained from the theoretical Yule-Walker equations. Then $\sqrt{N}(\widehat{S}_p(\omega) - S_p(\omega)) \sim N(0,\Psi_p)$.*

The covariance expression is quite complicated, and so is omitted here for convenience. The above result reverts back to the well known result for a regular process (e.g. [BRD]), at frequencies sufficiently removed from the point spectrum frequencies. At the point spectrum frequencies the mean becomes unbounded as the AR order approaches infinity. Furthermore, the variance at these frequencies is not as well behaved as at other frequencies. While we have not been able to arrive at results as both the model order, n, and data length, N approach infinity, our simulations suggest that at the point spectrum frequencies the condition that $n^3/N \to 0$, as opposed to $n^2/N \to 0$, is required for the variance to go to zero. A somewhat similar distinction of behavior at point spectrum frequencies was discovered for the MV spectral estimator.

Theorem 3.[LIU] *Let $\widehat{MV}_n(\omega)$ be the lagged-product estimator of $MV_n(\omega)$ defined in (9). Then $\sqrt{N}(\widehat{MV}_n(\omega) - MV_n(\omega) \sim N(0, Q_n(\omega))$ where $Q_n(\omega) = MV_n^4(\omega)\beta_n(\omega)^{tr}\Sigma\beta_n(\omega)$. The px1 vector $\beta_n(\omega)$ has ith component $\beta_i(\omega) = e_n^*(\omega)R_n^{-1}\Delta_{n,i-1}R_n^{-1}e_n(\omega)$ where $\Delta_{n,i}$ has $\pm$ith off-diagonals equal to one, and is zero elsewhere.*

The complex form of the variance of the MV(n) estimator has thus far precluded insight into its behavior. For this reason, we have explored this behavior via a variety of simulations in [LIU]. Foremost among our observations to date is that at non-point spectrum frequencies this variance goes to zero as $n \to \infty$ in the same manner as the mean does. While it is known that the mean has a -3 dB per doubling of n rate, the variance rate may not be the same. At point spectrum frequencies this variance converges to a nonzero value which is dependent on the local signal-to-noise ratio (SNR). While we have proposed detection schemes based on this family for the random process setting [SHL, [LYS], they are non-statistical in nature. The challenge here is the same as for any detection scheme. The more correlations one can use, the better the detection performance. But the statistical variability of higher order lags also increases with n. The above theorems provide the tools for balancing these factors.

One of the original goals of the research was to characterize the statistics of the AR(p) estimator of the periodic time/frequency spectrum associated with a wcs process. However, we discovered that any amount of period uncertainty in such a process will have the effect of destroying the time/frequency information. This behavior is summarized in the following theorem.

Theorem 4 [SHW]. *Let x(t) be a wcs process with period T_o, and let $S(\omega, t)$ be its associated spectrum. Let $\widehat{S}(\omega, t)$ be an estimator of $S(\omega, t)$ based on the autocorrelation estimator $\widehat{R}(t, t+\tau) = (1/m)\sum_{k=1}^{m} x(kT+t)x(kT+t+\tau)$. Then if $T \neq T_o$ or if T_o has any randomness over time, the estimator $\widehat{S}(\omega, t)$ will become independent of t as m approaches infinity.*

It is the behavior described in this theorem which guided a large part of our research, in an effort to arrive at advanced spectral methods for processes such as those associated with rotating machinery operating at a nominally constant speed, but having a measurable amount of period variability. The following theorem is related to our attempt to accommodate it.

Theorem 5 [LAS]. *Let $x(t) = sin(\omega t + \theta) + \nu(t)$, where $\nu(t)$ is white. Let $\widehat{\omega}$ be the least squares estimator of ω, based on $\{x(t)\}_1^n$. Then for large n, $\widehat{\omega}$ is normally distributed with mean and variance described in* [LAS].

The expressions for the mean and variance are a bit involved, and so are not given here. The reader is referred to [LAS]. This theorem is significant for two reasons. First, it provides a quantitative rationale for positioning a sinusoid (or any narrowband process) in the center of the frequency analysis range. Such positioning has long been noted to yield better AR descriptions of the spectral information, but only in a qualitative sense. Specifically, not only are both bias and variance minimized at this position, but the bias is exactly zero. Second, the theorem provided a guideline for development of an improved time-to-angle transformation described in [LAS]. Such a transformation can not only obviate the need for expensive hardware to accomplish the same thing, but can be applied to data that has been previously collected at uniform time sampling interval. Finally, we present a conjecture based on our latest investigation of the properties of the AR(n) spectral estimator applied to a mixed process.

Conjecture [LS2]. *The AR(p) spectral estimator for a mixed process converges to the continuous spectrum except at frequencies associated with the point spectrum, where it diverges at an asymptotic rate of p^2.*

This conjecture was arrived at after extensive simulations. It is important since it is commonly assumed that one can arrive at a point spectral estimate by dividing a continuous spectral estimate by p. This is true of both the MV(p) and p-windowed autocorrelation methods. The above theorem states that in the case of the AR(p) spectrum one must divide by p^2. The practical implication of this in relation to detection is immediate. By dividing by p^2 one not only converges to a constant proportional to the SNR, but one reduces the continuous spectrum asssociated with noise by 6 dB per doubling of p, as opposed to the traditional 3 dB.

C3. APPLICATIONS

The following application studies were conducted as part of the research effort. They were valuable in identification of real world issues that must be addressed to realize the potential of advanced spectral techniques.

Diesel Engine Vibration- Analysis of vibration associated with a diesel engine operating at nominally constant speed is the subject of [SHW]. That study led to Theorem 4 above, and to other investigations. For example, it pointed to some real world complications concerning the information in the MV and AR spectral estimators. It motivated an investigation of tone tracking algorithms, which led to Theorem 5. Finally, it demonstrated the difficulty of obtaining useful time/frequency spectral information in any setting involving sinusoids and period uncertainty.

Compressor Pressure- Analysis of the downstream pressure associated with a high speed compressor [VFS], [FSS] demonstrated the value of synchronous data collection in constructing time/frequency spectral information. But it also identified limitations of such hardware-based systems, in that they can lead to increasing phase errors throughout the period. This motivated, in part, our development of a software-based time-to-angle transformation method which can overcome this limitation.

Helicopter Gear Train Vibration- Analysis of this data set, which is provided by the U.S. Navy with the assistance of Westland and Penn State University, provided us with the opportunity to evaluate our time-to-angle transformation method, and to investigate the use of the above results in detecting faults in a well controlled experimental setting.

Upper Atmosphere- In an attempt to investigate the utility of the convergence-based MV method of analysis to a non-engineering problem, we addressed the problem of modeling the upper atmospheric wind profiles in a region of the South Pacific. In [WIS] it is shown that this approach led to not only quantifying the amount of

C4. BIBLIOGRAPHY

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[SHW] Sherman, P. J. and White, L. B. "Periodic spectral analysis of diesel vibration data," *Journal of the Acoustical Society of America*, **98**(6), 3285-3301, December 1995.

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[WIS] Wikle, C. and Sherman, P. J. "Using the family of MV spectra to determine periodicities in atmospheric data," *Journal of Climate*, **8**(10), 2352-2363, October 1995.

[WOR] Workshop on Signal Analysis Methods for Improved Condition Monitoring of Helicopter Drive Trains", 26-28 March, 1998, Virginia Beach, VA, Sponsored by the Office of Naval Research.

D. PUBLICATIONS

D1. Journal Papers

d1.1 Wikle, C. and Sherman, P. J. "Using the family of MV spectra to determine periodicities in atmospheric data," *Journal of Climate*, **8**(10), 2352-2363, October 1995.

d1.2 Sherman, P. J. and White, L. B. "Periodic spectral analysis of diesel vibration data," *Journal of the Acoustical Society of America*, **98**(6), 3285-3301, December 1995.

d1.3 Van Zante, D., Feddersen, R., Suarez, M. and Sherman, P. "The stochastic structure of downstream pressure from an axial compressor: Part I", *Mechanical Systems and Signal Processing*, **10**(4), 413-422, July 1996.

d1.4 Feddersen-Dudley, R., Suarez, M. and Sherman, P. J. "The stochastic structure of downstream pressure from an axial compressor: Part II", *Mechanical Systems and Signal Processing*, **10**(4), 423-438, July, 1996.

d1.5 Lyon, D.E., Sherman, P.J. and Frazho, A.E. "Application of the multichannel minimum variance spectra for analysis of harmonic random fields," *IEEE Transactions Signal Processing*, **44**(9), 2311-2318, September 1996.

D2. Journal Papers in Review

d2.1 Lau, S., Sherman, P.J. and White, L.B. "Asymptotic statistical properties of auto-regression in modeling processes with mixed spectrum", *Stochastic Processes & Applications.*

d2.1 Lau, S. and Sherman, P.J. "Statistical analysis of constrained AR(2) frequency estimators", *Journal of. Time Series Analysis.*

D3. Journal Papers in Preparation

d3.1 Liu, X.H. and Sherman, P.J. "Large sample statistics of the Capon spectrum estimator using lagged autocorrelations".

d3.2 Lau, S. and Sherman "Convergence rates of the MV and AR Spectra for mixed processes", *IEEE Trans. on Signal Processing* (in preparation).

D4. Published Conference and Workshop Papers

d4.1 Feddersen-Dudley, R., Suarez, M. and Sherman, P. J., "Statistical and stochastic analysis of blade-to-blade variability in pressure of a high speed compressor", *ASME Turbo-EXPO '95*, Houston, TX, June 5-8, 1995#.

d4.2 Spanjaard, J., White, L., Sherman, P. and Lau, S. "Periodic AR time-frequency analysis of rotating machinery with variable period" *Proceedings of the IEEE-SP International Symposium on Time-Frequency and Time-Scale Analysis*, 465-468, Paris, France, 18-21 June 1996.

d4.3 Sherman, P., White, L., Spanjaard, J. and Bitmead, R. "Asymptotic statistics of AR spectral estimators for processes containing mixed spectrum", *8th IEEE Signal Processing Workshop on Statistical and Array Processing*, 48-51, Corfu, Greece, 24-26 June 1996.

d4.4 Sherman, P. and Lau, S. "Asymptotic statistical properties of auto-regression in modeling processes with mixed spectrum", *1998 International Conference on Acoustics, Speech and Signal Processing*, Seattle, WA, 12-15 May 1998 **(in review).**

d4.5 Lau, S. and Sherman, P.J. "Periodic spectral analysis for processes with slowly varying period" *1997 International Conference on Acoustics, Speech and Signal Processing,* Seattle, WA, 12-15 May 1998 **(in review).**

D5. Unpublished Conference Presentations

d5.1 Lau, S.S. and Sherman, P.J. "Asymptotic statistical properties of the AR spectral estimator for random processes with mixed spectrum" *Midwest Meeting of the American Statistics Association*, 7-8 April 1997.

D6. ***Invited Presentations***

d6.1 Sherman, P. J. "A comprehensive methodology for analysis of signals from rotating machinery", Belfer Memorial Symposium on Mechanical Structures and Systems, *Technion Institute of Technology*, Haifa, Israel, May 15-17, 1995.

d6.2 Sherman, P. J. "A convergence-based approach for decomposition of mixed spectrum", *Australian Defence Science & Technology Organization*, November 10, 1995.

d6.3 Sherman, P. J. "Advanced spectral techniques for analysis of rotating machinery", *Korea Advanced Science & Technology Institute*, Center for Noise & Vibration Control, Science Town, Taejon, Korea, January 20, 1995.

d6.4 Sherman, P.J. "A frequency domain investigation of the planet gear inner race corrosion spalling in a helicopter gear train" *The Office of Naval Research*, 7 March 1997.

d6.4 Sherman, P.J. "Signal processing issues concerning nominally periodic processes with applications to rotating machinery" *U.S./Australian Workshop on Defense Signal Processing*, Victor Harbor, South Australia, 25-27 June 1997.

d6.5 Sherman, P.J. "Signal processing research related to rotating machniery" *Symposium on Advances in Signal Processing*, The Cooperative Research Center for Sensor Signal and Information Processing, Adelaide, SA, 30 June-1 July, 1997.

E. GRADUATE STUDENTS

MS (Creative Component) Students in Statistics

e.1.Wikle, C. "Stochastic modelling of atmospheric phenomena", August 1994, [joint with Meteorology].

e.2.Liu, X. "Statistical analysis of the family of minimum variance spectra", October 1997.

e.3.Lau, S. "Statistics of AR(p) models in relation to periodic and quasi-periodic processes as the order $p \to \infty$", expected completion date- October 1997.

MS (Thesis) Students in Engineering

e.4. Lau, S. "Periodic and quasi-periodic random processes with applications" M.S. Thesis, Department of Electrical Engineering, Iowa State University, May, 1997.

F. COLLABORATIONS

F1. Research at Host Institutions

	Host	*Location*	*Dates*
1.	Aus. Natl. Univ.	Canberra, Aus.	7/11/92-8/2/91
2.	DSTO (defense dept)	Adelaide, Aus.	8/3/92-8/20/92
3.	DSTO	Adelaide, Aus	7/21/93-8/13/93
4.	DSTO/ANU	Adelaide/Canberra	7/95-12/95
5.	Korea Adv. Inst. of Science & Tech.	Science Town Taejon, Korea	1/19-1/26/96

F2. Conference and Workshop Involvement

- Invited to be part of a committee to organize a U.S./Australia signal processing workshop, held 25-27 June 1997. The workshop theme was development and application of advanced signal processing for industry and Defense applications.

- Invited to participate in NSF/ONR workshop "Signal processing for manufacturing and machine maintenance", Alexandria, VA, 13-15 March 1996.

- Invited to organize and chair a special session on rotating machinery at the next *IEEE Workshop on Statistical Signal and Array Processing*, to be held in Portland, OR in June 1998.

- Principal organizer of an ONR/AFOSR-sponsored workshop on helicopter diagnostics to be held March 26-28, 1998.

G. WEB SITE INFORMATION

A web site is currently under development. It will contain (i) this report, (ii) our *Matlab*-based virtual analyzer application, and (iii) links to sites such as that related to the helicopter data [WOR].